QUANTITATIVE ELECTROMAGNETIC MODELING AND NDE OF CARBON-CARBON COMPOSITES

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INTRODUCTION

There is much need for investigating the use of eddy-current inspection with advanced composite materials, including graphite-epoxy and carbon-carbon. One of the problems in evaluating the performance of eddy-current inspection is that it is often difficult to characterize the conductivity of the fiber composite material. For example, when the material is composed of conducting fibers and a nonconducting matrix, as is the case with graphite-epoxy, the overall conductivity is a complicated quantity that depends on fiber conductivity, fiber density, fiber layup order (sample geometry), and the frequency at which the eddy-currents are being excited. Dependency on frequency and layup order, in particular, give the investigator much difficulty in interpreting any eddy-current data from experiments. If these two factors cause a weak effect, there may be a suitable range of frequencies for inspecting the material via application of somewhat standard techniques.

Presented here are eddy-current inspection and modeling techniques for carbon-carbon and other advanced composites. These experiments give much insight into the conductivity characteristics of many materials, and thereby allow one to adequately interpret many of the experimental data from samples. For example, it was shown that under some conditions, carbon-carbon material can behave as though it is an homogeneous bulk conductor (modeled like a metal), while under similar conditions, a sample of graphite-epoxy must be modeled in a much more complicated fashion. This observation leads to many implications about inspection techniques that are applicable for detection of structure, flaws, and conductivity.

The EMF measurements are made using inductive sensors, excited by various innovative current sources. Measurements in the range of 50KHz to 50MHz indicate conductivity, oxidation holes, and weave and matrix structure of the material. This paper presents laboratory data acquired from actual samples of material and calculations from various computer models used to predict electromagnetic fields and material's sometimes-anisotropic conductivity. From the calculations and laboratory data it was possible to infer such things as conductivity and proper fiber layup order in multi-layer composites. Calculations also relate the electromagnetic shielding properties of a few different materials to their layup geometries. Laboratory data exist that confirm most of the model

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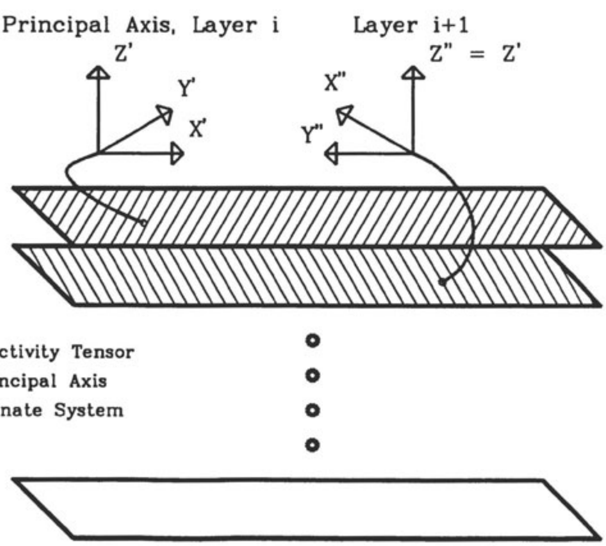
calculations, giving a strong indication that the models are accurate for these materials.

EXPERIMENTAL PROCEDURE

Multi-frequency phase and amplitude data were collected using a computer-controlled laboratory setup. Measurements were made using a ''bi-static'' arrangement, in which the sensor passively measured the magnetic field in the presence of a separately driven exciting coil. Through-transmission measurements were made, in which the EMF was measured on one side of a slab of material, while the exciting coil was on the other side of the slab. The exciting coil was fixed; scanning was done with the sensor. Reflection measurements are also possible to perform and model, but were not used for the purpose of this paper.

The through-transmission measurements are modeled using one of two different computer models; one model takes into account the layup geometry of a multi-layer, possibly anisotropic sample, and the other model treats the sample as a bulk conductor [1]. These two models will be referred to as the ''multi-layer'' and ''bulk'' models, respectively. Certain materials can be practically treated as a bulk conductor; others must have their multi-layer geometry taken into account. Parameters such as sample thickness and excitation frequency can be varied in either model. When X and Y are defined to lie in the plane of the sample, and Z is normal to the sample, the conductivity of the material in X Y and Z must be specified in the bulk model (similar to one layer of Figure 1). The multilayer model can have a distinct X and Y conductivity for each layer, and each layer is given a rotation angle in the X-Y plane, as shown in Figure 1. The output of the computer model is the EMF predicted in the presence of a the sample (what a nearby sensor would measure). The computed EMF is directly compared with the laboratory measurements; EMF scale normalization is required to account for differences in excitation currents and amplifier gain.



$$\begin{bmatrix} \sigma_{xx} & 0 & 0 \\ 0 & \sigma_{YY} & 0 \\ 0 & 0 & \sigma_{zz} \end{bmatrix}$$

Fig. 1. Drawing of ''multi-layer'' model. The bulk model treats material as a single layer; the multi-layer model allows specification of the layer-by-layer geometry of the material. The conductivity tensor specifies the conductivity in the X Y and Z directions of the layer's principal coordinate system.

Conductivities of samples are inferred by modeling the experiment with one of the two models described above, and varying model parameters until there is good agreement between experimental data and model predictions. In particular, the thickness and other physical parameters are measured using various instruments leaving only the conductivity to vary in the model. It is assumed that a match between experiment and model can be obtained by varying the conductivity in the model. When a model calculation predicts a field higher in magnitude than the EMF measured in the laboratory, the conductivity in the model is increased so as to decrease the transmitted field. Through trial and error, a match between experiment and theory is obtained, implying the conductivity.

Delaminations were modeled using the multi-layer model. Calculations were made with a ''control'' 36-layer model of graphite-epoxy material, then with a 37-layer model that was the same as the previous calculation except that a new layer of ''air'' was introduced. The calculations were compared by subtracting the signals, point-by-point, and comparing their difference with the control. The model was of a sample containing thin Teflon sheets between layers. This panel with simulated delaminations was also inspected in the laboratory. The layup ordering was alternating +45/-45 degrees (a well-shuffled ''deck''). In a separate experiment, the layup was changed to nine@45, nine@-45, nine@45, and nine@-45, which is essentially the same thing as four thick layers.

The conductivity of a sample of carbon-carbon composite was inferred using several steps. First, laboratory measurements were made on a known-conductivity sample (aluminum) and compared with bulk-model calculations to determine the scale factors to compensate for excitation current and system gain. Next, measurements were made on another known-conductivity sample (copper) to test that results against model. The laboratory data were scaled by the factors determined from the aluminum sample and compared with the model predictions. Next, a measurement was made on the unknown-conductivity sample of carbon-carbon. Finally, the conductivity in the model was varied until the predicted peak magnitude of EMF agreed with the model calculation at a single frequency. A similar experiment was performed using a sample of graphite-epoxy composite.

EXPERIMENTAL RESULTS

Figures 2 and 3 show the results of the experiments for measuring the conductivity of the carbon-carbon material. Model calculations are plotted using dashed lines and laboratory data are solid. The left side of Figure 2 is the calibration data from a sample of aluminum foil. Scale factors were determined from these data so that other laboratory data could be properly normalized to compare with model calculations. The other plot in Figure 2 is the result of applying those scale factors to measurements from a sample of copper foil. Thickness measurement of the copper was crude, but there was sufficient agreement between laboratory and model. Figure 3 (left) is the model and laboratory data for a sample of carbon-carbon, after the conductivity in the model has been adjusted to match the lab measurements at one frequency. The right side of Figure 3 is the laboratory and model data for a sample of graphite-epoxy material.

The difference signal and control signal from a modeled delamination areo presented in Figures 4 and 5. A delamination was simulated by introducing a new layer of ''air,'' modeled as having very small conductivities in X Y and Z. The simulated delamination was also measured in the laboratory; results have been previously presented [2]. The laboratory ''delaminations'' were thin sheets of Teflon between layers of a multi-layer graphite-epoxy. The model has well-mixed (alternating

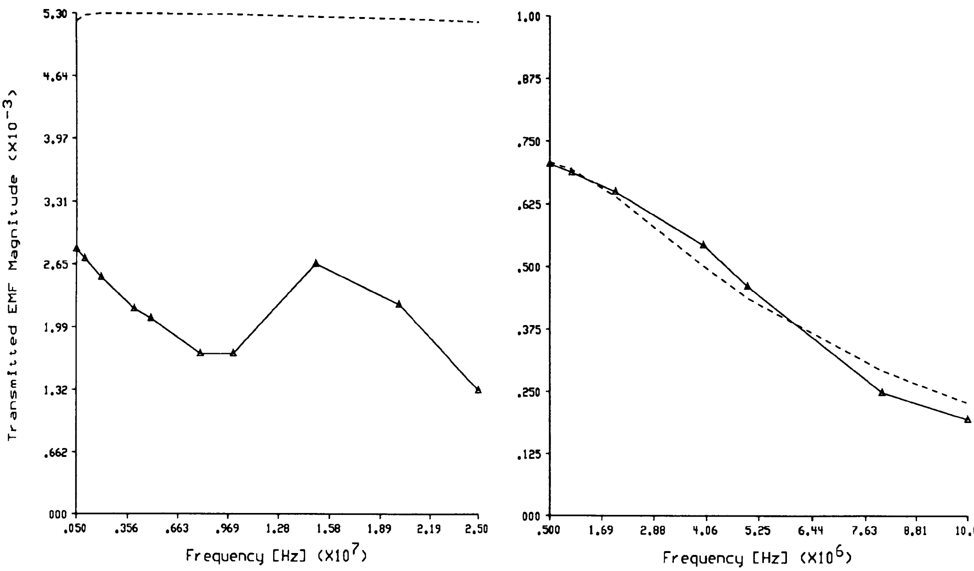


Fig. 2. Model and experiment: calibration and testing of conductivity measurements. On the left is the calibration measurement from aluminum foil; The plot on the right is a test using a known sample of thin copper. The model calculations are dashed; laboratory data are solid. The values represent the peak EMF transmitted through the sample.

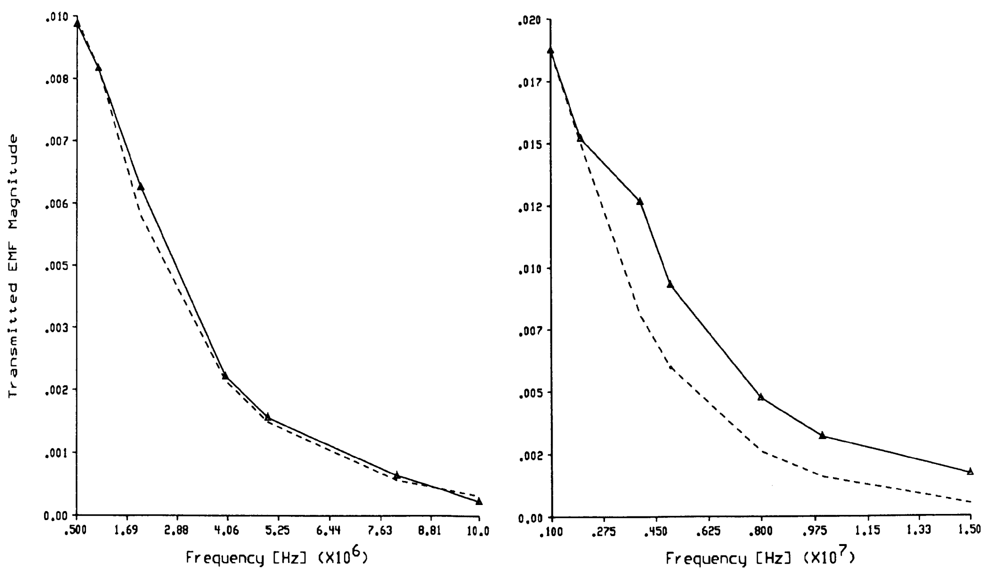


Fig. 3. Through-transmission EMF magnitudes for carbon-carbon and graphite-epoxy. (left) is from carbon-carbon; (right) is graphite-epoxy. The model calculations are dashed; laboratory data are solid. Both materials were modeled using the bulk model, which appears to fail for the graphite-epoxy.

+45/-45 degrees) layers. The exact layup of the laboratory sample is not known, but appears to be not as well-mixed. Another separate calculation was performed using an identical set of 36 layers, except that the layup ordering was changed so that there were four stacks of nine layers, each group of having nine identical layers. The calculations of EMF magnitude transmitted through the ''9-9-9-9'' sample are presented in Figure 6. The layers are identical to those used for Figure 4, except they were stacked in a different order.

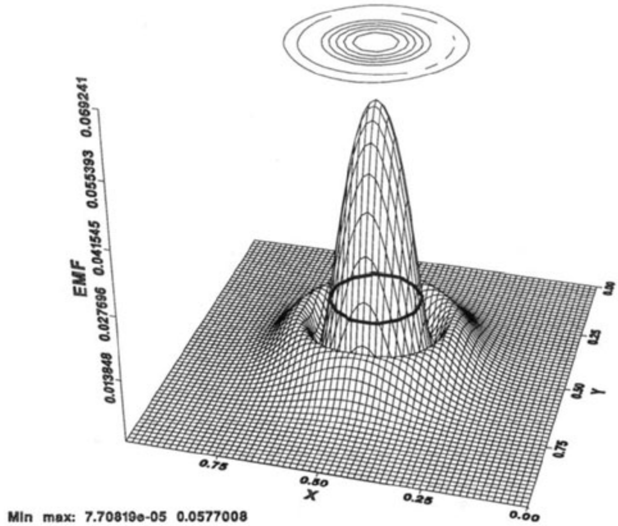


Fig. 4. Signals transmitted through a multi-layer composite of 36 alternating +45/-45 degree layers. Zero-to-peak magnitude is approximately 5.8e-2 [EMF]. Orbits represent equi-potential contours.

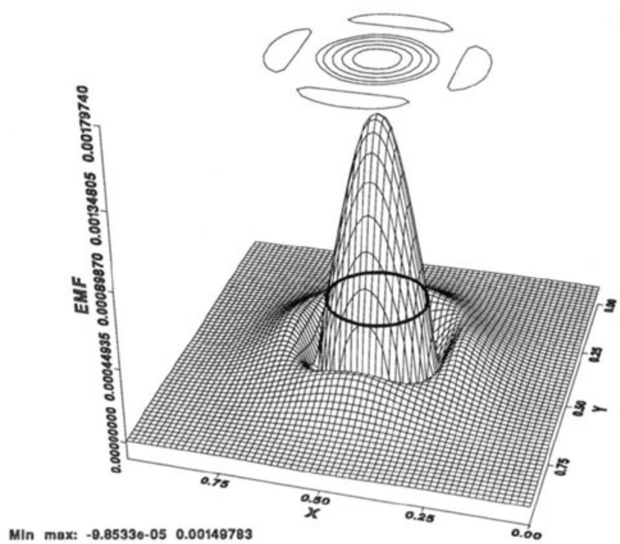


Fig. 5. Difference between signal of Figure 4 and a 37-layer sample, identical except for the introduction of a layer of ''air.'' The peak EMF value is approximately 1.5e-3.

Similar characteristics have been observed in the laboratory, some of which have been previously reported [2]. Laboratory measurements that demonstrate, at least qualitatively, some of the features of this model calculation are presented in Figure 7. Unfortunately, the layup order was unknown for the lab sample, so it was not possible to model the geometry. Introducing a layer of air does not significantly change the geometry of the sample but causes a noticeable difference in signal. What about rotating one of the layers to an improper orientation angle?

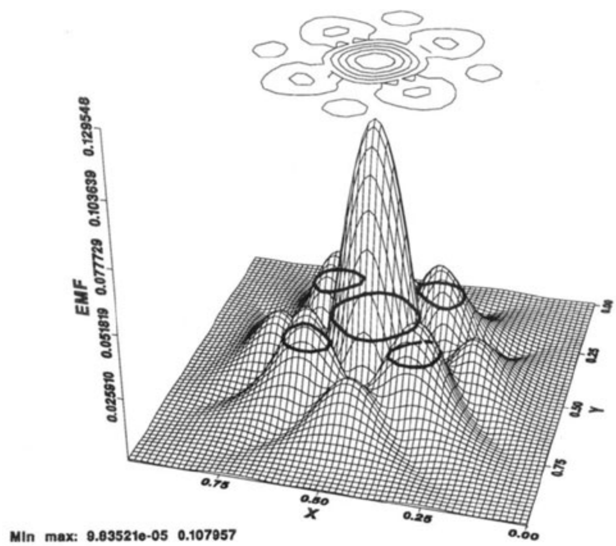


Fig. 6. Calculation of EMF magnitude transmitted through a 36-layer sample having four groups of nine layers. The four groups are oriented +45/-45/+45/-45 degrees. The peak EMF magnitude is approximately 1.1e-1.

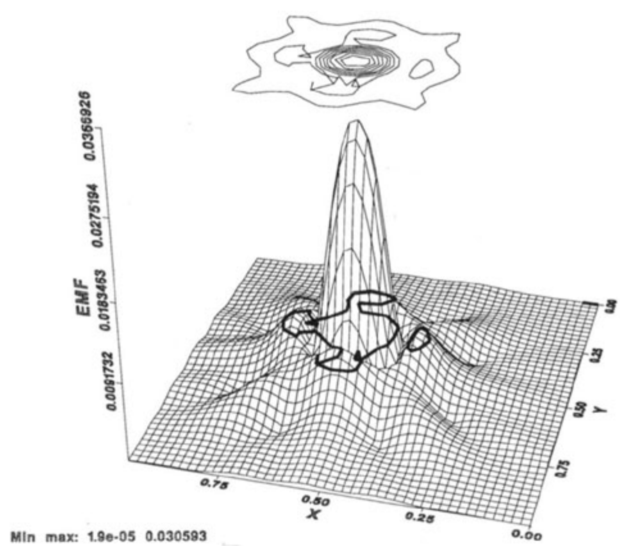


Fig. 7. Laboratory measurements that have some of the same features of the model calculations from Figure 6. In this case, the layup order was unknown.

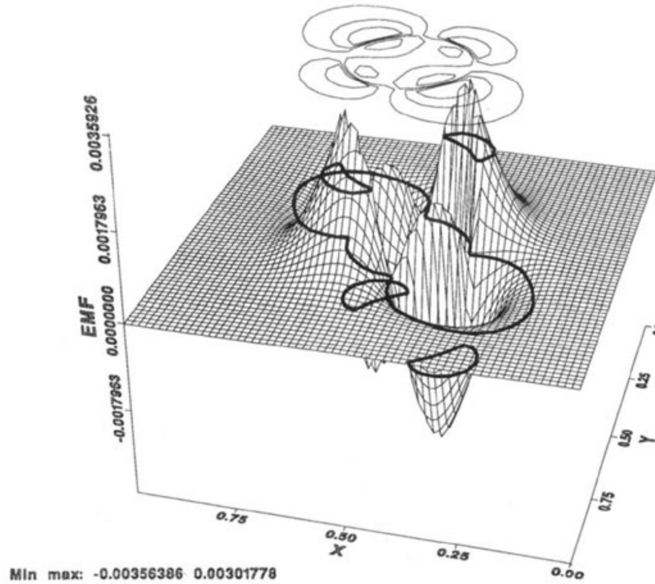


Fig. 8. Difference in EMF magnitude transmitted through a 36-layer sample of alternating +45/-45 degrees, except for layer eighteen, which is rotated out of place by ninety degrees. The peak-to-peak EMF magnitude is approximately 7.1e-3

Figure 8 shows the difference signal resulting when the eighteenth layer is rotated out of whack by ninety degrees. Compare the magnitude of this difference plot with the control signal magnitude of Figure 4.

CONCLUSIONS

Our samples of carbon-carbon material were best modeled using the bulk model of conductivity. In the bulk model, the conductivity tensor is the same at every (X,Y,Z) position inside the material, unlike the multi-layer model, in which the conductivity tensor is a function of Z (see Figure 1). The bulk model has the advantage of requiring less computation than the multi-layer model. Laboratory carbon-carbon data deviations from the model calculations become relatively large at the high frequencies. This deviation from the bulk-conductivity model can probably be explained by experimental error, since the magnitude of the transmitted field dies out at the high frequencies. On the other hand, it is possible that carbon-carbon no longer behaves as a bulk conductor when the skin depth gets to be very small (in this case, several layers thick). If so, the multi-layer model would probably be useful at high frequencies. There may be other factors affecting the transmitted field besides the conductivity, for example, the dielectric properties of the material. It is assumed that these possible effects are negligible. It is difficult to quantify skin depth when a conductor is anisotropic since there may be two or more different ''skin depths'' as a result of the different conductivities in the various material directions. It seems reasonable, however, to assume that the bulk model works well on carbon-carbon, as long as the skin depth is large enough (at least a couple of layers). The implication is that standard inspection techniques, such as eddy-current methods of detecting coating thickness, should be directly applicable to carbon-carbon, as long as the frequency is appropriately adjusted to compensate for the different skin depth, and the resulting skin depth is not too small.

The relatively simple bulk model does not work well for the graphite-epoxy samples that were inspected. The graphite-epoxy samples were best modeled using the more detailed multi-layer model. No conductivities used in the bulk model seem to give rise to what one might call ''fourfold'' or ''multi-lobe'' symmetry that is often encountered in laboratory data when a multi-layer anisotropic sample is excited with a circular current. The multi-lobe symmetry, however, is predicted in the multi-layer model with certain layup configurations, as seen in Figure 6. Eddy currents in the Z direction are predicted by the model for multi-layer anisotropic materials, and may explain the multi-lobe symmetry. The layup ordering of the material has a profound effect on the field measured near sample. This phenomenon is dramatically demonstrated by one experiment in which a simple renumbering of the thirty-six layers composing a sample caused the transmitted field magnitude to change by a factor of two (compare magnitudes in Figures 4 and 6). One implication of this experiment is that there is a ''right'' way and a ''wrong'' way to orient layers in a sample when you wish to obtain the best (or worst) electromagnetic shielding properties possible (e.g. in making stealth aircraft).

Calculations and laboratory data indicate that it is possible to detect delaminations in graphite-epoxy material using eddy-currents. The multi-layer model predicted a subtle effect resulting from a simulated delamination. Laboratory data agreed with this prediction in that some simulated delaminations caused a detectable change in transmitted signal [2]. The model predicts the difference in the transmitted signal in the presence of a delamination to be about 2 percent of the peak signal, at the maximum point. This is probably challenging to detect, depending on how much change in signal results from the ''normal'' sample variations. A misplaced layer results in a much stronger difference signal. The case presented here has a peak-to-peak difference that is more than ten percent of the peak signal. With further development of theory, it should be possible to construct an eddy-current instrument for verifying layup orientation and order.

Results presented here raise almost as many questions as they answer. For example, the mechanism for producing multi-lobe symmetry has not been explained; it has only been shown that such symmetry exists. An explanation of this phenomenon would surely prove useful in understanding and using eddy-currents in layered media. Further study and experimentation will result in an improved and more useful model and a greater understanding of eddy-current behavior in advanced composites.

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